Antiproton Production in p+d Reaction at Subthreshold Energies

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Abstract

An enhancement of antiprotons produced in $p+d$ reaction in comparison with ones in $p+p$ elementary reaction is investigated. In the neighborhood of subthreshold energy the enhancement is caused by the difference of available energies for antiproton production. The cross section in $p+d$ reaction, on the other hand, becomes just twice of the one in elementary $p+p$ reaction at the incident energy far from the threshold energy when non-nucleonic components in deuteron target are not considered.

Antiproton productions have been one of the most interesting subthreshold production process since they have been observed in proton-nucleus reactions more than thirty years ago [1-3].

About a decade ago, the production of antiprotons at subthreshold in nucleus-nucleus was observed [4-6] and various models have been proposed to explain experimental data, models based on the assumption of kinetic and chemical equilibrium [7-9], and models in terms of multiple interactions [10,11]. First fully relativistic transport calculations for antiproton production including antiproton annihilation as well as the change of the quasi-particle properties in the medium have shown that the antiproton yields for $p+A$ and $A+A$ can be well reproduced simultaneously when employing proper self energies for the baryons in the dense medium (the relativistic BUU approach)[12-16].

Five years ago the problem was taken up at KEK[17] aiming to carry out measurements of subthreshold antiproton productions with light ions such as d and α . In particular, the cross section ratio of antiproton productions between proton induced and deuteron induced reactions is insensitive to uncertainties of antiproton reabsorption in a target nucleus and of the antiproton production cross section in elementary NN interaction near the subthrshold, which give large ambiguity in any theoretical model calculation. The most surprising finding was an enormous enhancement of antiproton productions in $d+A$ reaction at lower incident energies per nucleon and the existence of non-nucleon components in the deuteron wave function was suggested to cure the situation.

To explore this suggestion the BUU approach group performed calculations employing the deuteron wave function from which had been fitted to deuteron fragmentation data at high energy and noted that the present data do not yet provide clear evidence for non-nucleon components in the deuteron wave function[18].

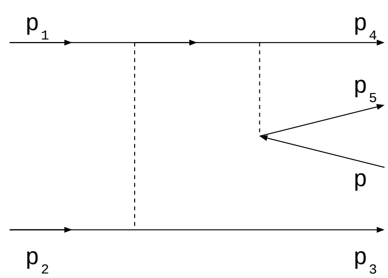

Figure 1: The diagram for antiproton producing mechanism in proton-proton collision.

In this note we take up the most simple reaction $p+d \rightarrow \bar{p}$ and clarify the enhancement of antiproton productions in comparison with the elementary process when we do not consider non-nucleonic components in the deuteron wave function. First, we treat the elementary $\bar{p}$ production case, $p+p \rightarrow \bar{p}ppp$. The Feynman diagram is shown in Fig.1 where the four-dimensional momenta of particles are also indicated. The total cross section is described as follows,

$$\sigma = \frac{1}{4\sqrt{(p_1 \cdot p_2)^2 - {m_1}^2{m_2}^2}} \frac{1}{(2\pi)^8} \int \frac{d\boldsymbol{p}_3}{2E_3}\frac{d\boldsymbol{p}_4}{2E_4}\frac{d\boldsymbol{p}_5}{2E_5}\frac{d\boldsymbol{p}}{2E} | \, T_{pp\rightarrow\bar{p}ppp} \, |^2$$
$$\times \delta(p_1 + p_2 - p_3 - p_4 - p_5 - p) \qquad (1)$$

where m_i $(i = 1 \sim 5)$ and mass of antiproton are proton mass M, and E_i *and* E are on shell proton and antiproton energies respectively. The absolute square of invariant amplitude
$| \, T_{pp\rightarrow\bar{p}ppp} \, |^2$ is given

$$| \, T_{pp\rightarrow\bar{p}ppp} \, |^2 \cong T_{pp}^2 \cdot (2M) \cdot (2M) \qquad (2)$$

We assume that the cross section of antiproton production in low incident energies near the threshold energy is approximately proportion to the four body phase space. Then, we take a constant value for the absolute square of invariant amplitude which is fitted to data of antiproton production in the neighborhood of the threshold energy as shown in Fig.2. The obtained constant value of $| \, T_{pp\rightarrow\bar{p}ppp} \, |^2$ can be separated into two factors , the incident proton part emitting antiprotons T_{pp}^2 and the target proton part $(2M)\cdot(2M)$ which approximates the square of normalization factor, $(2E_2 \,) \cdot (2E_3 \,)$, of the wave functions before and after the reaction. This T_{pp}^2 is inserted into the incident proton part in an absolute square of invariant amplitude $T_{pd\rightarrow\bar{p}}$ which describes $\bar{p}$ productions in pd interaction.

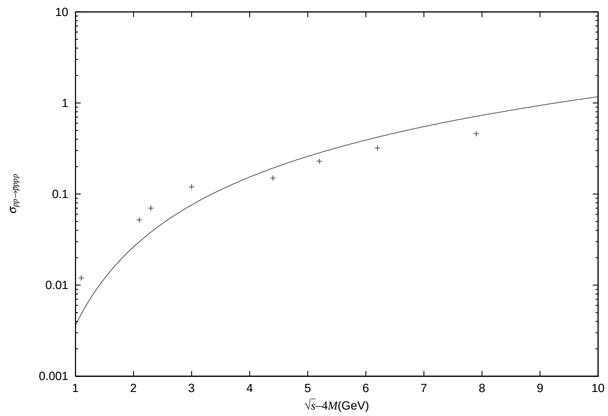

Figure 2: The cross section for antiproton production in proton-proton collisions,circles and squares refered from ref.19 and ref.20,respectively. The line indicates our parameterization of the cross section as described in the text.

Next, we proceed to reactions $p + d \to \bar{p}ppd$ and $p + d \to \bar{p}pppn$ of which Feynman diagrams are shown in Fig.3. Both of diagrams show that a fast proton collides with a deuteron at rest and products an antiproton while the target deuteron keeps a bound state or breaks up in two nucleons. In this note we treat the internal motion of deuteron non-relativisticaly and use the deuteron wave function which is solved with the Reid soft core potential by the superposition of a few Gaussians [19].

$$\tilde{\phi}_d(\boldsymbol{p}) \;=\; \sum_{i=1}^{3} a_i e^{-\boldsymbol{p}^2/d_i^2} \tag{3}$$

where the parameters a_i and d_i are given as

$$\begin{aligned} a_1 &= 540(GeV)^{-3/2}, & d_1 &= 0.058(GeV), \\ a_2 &= 72, & d_2 &= 0.158, \\ a_3 &= 4.4. & d_3 &= 0.58. \end{aligned}$$

Applying this wave function to the deuteron target in pd collision the observed energy spectra of backward proton are well reproduced [20]. The absolute square of amplitude of $\mid T_{pd\to\bar{p}ppd}\mid^2$ is given

$$\mid T_{pd\to\bar{p}ppd}\mid^2 \;\cong\; T_{pp}^2 \cdot (2m_d)\cdot(2m_d)\cdot\left(f_a((\boldsymbol{p}_3-\boldsymbol{p}_2)^2)\right)^2 \tag{4}$$

where m_d denotes the mass of deuteron and $\left(f_a((\boldsymbol{p}_3-\boldsymbol{p}_2)^2)\right)^2$ is a probability that the internal motion in the target deuteron absorbs a momentum $\boldsymbol{p}_3-\boldsymbol{p}_2$ transferrd from the incident proton,

$$f_a(\boldsymbol{q}^2) \;=\; \frac{1}{(2\pi)^2}\int d\boldsymbol{p\prime}\phi(\boldsymbol{p\prime})\phi(\boldsymbol{p\prime}-\frac{1}{2}\boldsymbol{q})+\phi(\boldsymbol{p\prime}+\frac{1}{2}\boldsymbol{q})] \tag{5}$$

$$\boldsymbol{q} = \boldsymbol{p}_3 - \boldsymbol{p}_2$$

Also, we obtain $\mid T_{pd \to \bar{p}pppn} \mid^2$ of the deuteron breakup process as follows

$$\mid T_{pd \to \bar{p}pppn} \mid^2 \;\cong\; T_{pp}^2 \cdot (2m_d) \cdot (2M)^2 (f_b(\boldsymbol{p}_2; \boldsymbol{p}_3, \boldsymbol{p}_6))^2 \tag{6}$$

$$f_b(\boldsymbol{p}_2; \boldsymbol{p}_3, \boldsymbol{p}_6) \;=\; \phi(\boldsymbol{p}_3 - \frac{1}{2}\boldsymbol{p}_2) + \phi(\boldsymbol{p}_6 - \frac{1}{2}\boldsymbol{p}_2) \tag{7}$$

where $(f_b(\boldsymbol{p}_2; \boldsymbol{p}_3, \boldsymbol{p}_6))^2$ is proportion to a probability that either nucleon in target deuteron accepts a momentum transferrd from the incident proton. Thus, we obtain the invariant cross section of $\bar{p}$-productions in $p + d$ reaction,

$$\begin{aligned}
\sigma \;=&\; \frac{1}{4\sqrt{(p_1 \cdot p_2)^2 - {m_1}^2 {m_2}^2}} \frac{1}{(2\pi)^8} \Big[\; T_{pp}^2 \cdot (2m_d) \cdot (2m_d) \\
&\times \int \frac{d\boldsymbol{p}_3}{2E_3} \frac{d\boldsymbol{p}_4}{2E_4} \frac{d\boldsymbol{p}_5}{2E_5} \frac{d\boldsymbol{p}}{2E} (f_a((\boldsymbol{p}_3 - \boldsymbol{p}_2)^2))^2 \delta(p_1 + p_2 - p_3 - p_4 - p_5 - p) \\
&+ T_{pp}^2 \cdot 2m_d \cdot (2M)^2 \int \frac{1}{(2\pi)^3} \frac{d\boldsymbol{p}_3}{2E_3} \frac{d\boldsymbol{p}_4}{2E_4} \frac{d\boldsymbol{p}_5}{2E_5} \frac{d\boldsymbol{p}_6}{2E_6} \frac{d\boldsymbol{p}}{2E} (f_b((\boldsymbol{p}_2; \boldsymbol{p}_3, \boldsymbol{p}_6)^2))^2 \\
&\times \delta(p_1 + p_2 - p_3 - p_4 - p_5 - p_6 - p) \Big]
\end{aligned} \tag{8}$$

The four-momentum of deuteron is defined as $p_2 = (E_2 - \epsilon, \boldsymbol{p}_2)$ where E_2 and ϵ are the center of mass energy and the relative binding energy respectively.

The figure 4 shows the ratio of total cross sections of $p + p$ and $p + d$ reactions as a function of the incident energy. The available energies for incident energy are $7M$ and $5M + \epsilon$ for $p + p$ and $p + d$ reactions respectively.The latter is the subthreshold energy for p production in pd interaction. We note here that the available energy of incident deuteron energy is also $5M + \epsilon$ per nucleon when the deuteron collides with the proton target at rest.

At low incident energies in the neighborhood of threshold of $p + p \to \bar{p}$ reaction, the enormous enhancement of the ratio of antiprotons produced in $p + d$ reaction and ones in $p + p$ reaction is reasonably caused due to the difference of the available energies for $\bar{p}$ productions. The figure 5 shows two processes in $p + d$ reaction, the deuteron bound process and the deuteron breakup process. The deuteron breakup process produces more antiprotons than the bound process since the former has a five-body phase space larger than a four-body phase space in the latter process and since the transition matrix of the former process includes an internal wave function of deuteron while the one of the latter process has an absolute square of wave function of deuteron.

We take notice of the cross section of the deuteron breakup process, the second term in equation (8). The cross section takes the maximum value when two broken-up nucleons have respectively a half of momentum of deuteron before the collision with proton. In

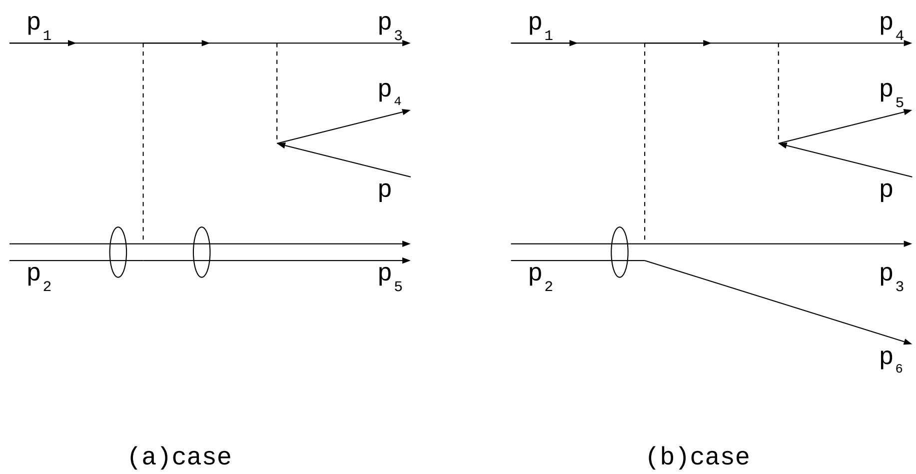

Figure 3: The diagram for antiproton producing mechanism in proton-deuteron collision. The projectile proton collides with one of the two nucleons in deuteron and produces antiprotons in two processes (a) $P + d \rightarrow \bar{p}ppd$ (deuteron bound) and (b) $p + d \rightarrow \bar{p}pppn$(deuteron breakup).

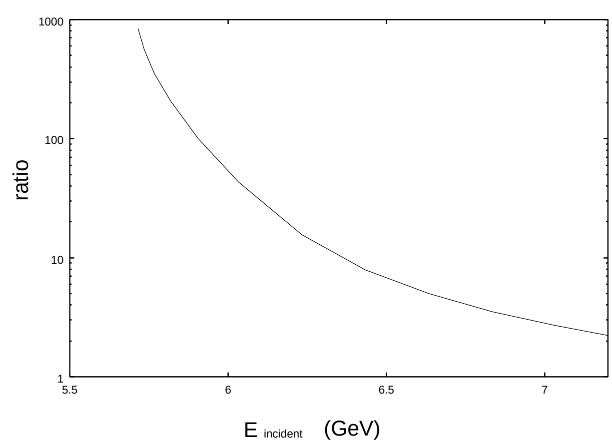

Figure 4: The ratio of antiproton productions in pp and pd collisions as a function of the incident energy.

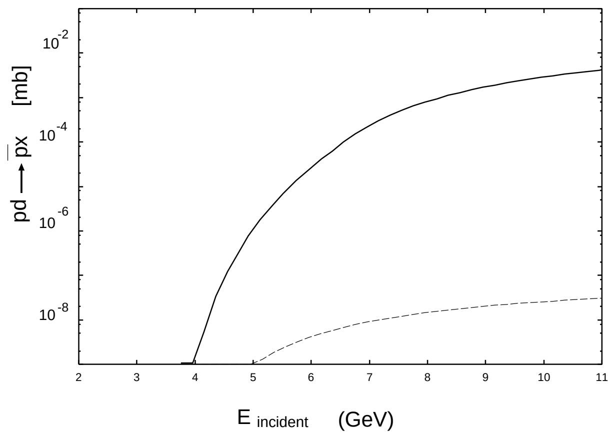

Figure 5: The cross sections as a function of the incident energy. The solid line and the dashed line indicate the deuteron breakup process and the deuteron bound process, respectively.

the laboratory system ($\boldsymbol{p}_2 = 0, E = m_d$), if we replace the two internal wave functions in Eq.(8) with δ -functions,

$$\phi(\boldsymbol{p}_3) \rightarrow (2\pi)^{\frac{3}{2}}\delta(\boldsymbol{p}_3) \quad and \quad \phi(\boldsymbol{p}_6) \rightarrow (2\pi)^{\frac{3}{2}}\delta(\boldsymbol{p}_6) \tag{9}$$

the cross section is rewritten as follows,

$$\begin{aligned}
\sigma \; = \; & \frac{1}{4}\frac{1}{v_{rel}}\frac{1}{E_1}\frac{1}{(2\pi)^8}\cdot T_{pp}^2 \cdot 4M \\
& \Big[\int \frac{d\boldsymbol{p}_3}{2E_3}\frac{d\boldsymbol{p}_4}{2E_4}\frac{d\boldsymbol{p}_5}{2E_5}\frac{d\boldsymbol{p}}{2E}\delta(E_1 + m_d - M - E_3 - E_4 - E_5 - E) \\
& \times\delta(\boldsymbol{p}_1 - \boldsymbol{p}_3 - \boldsymbol{p}_4 - \boldsymbol{p}_5 - \boldsymbol{p}) \\
& + \int \frac{d\boldsymbol{p}_6}{2E_6}\frac{d\boldsymbol{p}_4}{2E_4}\frac{d\boldsymbol{p}_5}{2E_5}\frac{d\boldsymbol{p}}{2E}\delta(E_1 + m_d - M - E_6 - E_4 - E_5 - E) \\
& \times\delta(\boldsymbol{p}_1 - \boldsymbol{p}_6 - \boldsymbol{p}_4 - \boldsymbol{p}_5 - \boldsymbol{p})\Big]
\end{aligned} \tag{10}$$

where v_{rel} denotes the relative velocity between incident proton and target deuteron. This cross section is just twice of the one in the elementary process if the small binding energy of deuteron is not taken into account. The interference term disappears, since this term corresponds to a deuteron spectator process and the energy-momentum conservation for residual four nucleons can not be satisfied because four nucleons are on shell. Then, the ratio of cross sections approaches to a factor two as the incident energy goes up far away from the threshold energy. We are going to calculate the differential cross section including non-nucleonic components in deuteron internal state.

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